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Scattering processes in the structures with one-dimensional lateral superlattice

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1 Introduction

The semiconductor nanostructures with artificial periodic potential in lateral plane are considered as very attractive objects in both fundamental and applied investigations. To construct a periodic potential relief, various methods are employed [1, 2]. Let us consider the structures with lateral superlattice created by wire-like doping of a vicinal i-GaAs surface [3, 4]. After deposition of a fraction of Si (or Sn) monolayer on the i-GaAs δ-doping plane having well-formed set of monolayer steps, both migration process of Si (Sn) adatoms and their segregation to the step edges are observed; thus we deal with the self-organized wire-like doping. The typical terrace step width is $\sim$ 8 nm for Si doping, $\sim$ 50 nm for Sn doping on vicinal (001) GaAs surfaces. The overall view of the structure considered is shown in Fig. 1, Fig. 2 represents the calculated potential and the electron distribution in the GaAs(0.3°, δ-Sn) structure for the doping level $N_D \approx 1.8 \times 10^{12}$ cm^{-2}. The distribution law of impurity atoms on the step of vicinal plane was approximated by Gaussian law: $N_D(x) \sim \exp\{-(x - d/2)^2/2\sigma^2\}$, where d is the width of the vicinal plane step and σ is the standard deviation of distribution. The width of terrace steps is set to be 53 nm, which corresponds to the case of the 0.3°-off GaAs(001) surface.

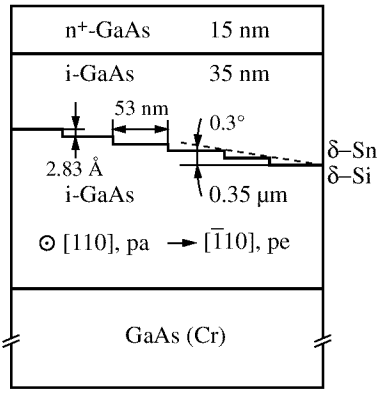

Fig. 1. The overall view of the structure with δ-Sn layer on i-GaAs vicinal plane.

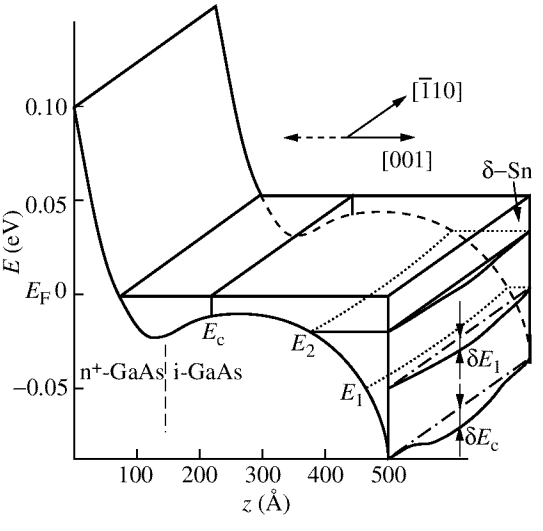

Fig. 2. The band diagram $E_c(x, z)$ and electron wave functions in the GaAs(0.3°, δ-Sn) structure. The modulation of conduction band edge E_c and size-quantized levels E_1, E_2 in the [1̄10] direction is shown.

The structures of this kind revealed the anomalies of kinetic effects [4]: the "giant" negative magnetoresistance (up to 28% for the [110] direction) and the anisotropy of conductivity in the whole ranges of both electric fields $E = 0-7$ kV/cm, magnetic fields $B = 0-40$ T, temperatures $T = 0.39-293$ K. To explain the anomalies observed complex investigations of scattering mechanisms of electrons in the GaAs(0.3°, δ-Sn) structure are needed.

The aim of this work is the modeling of various scattering processes in the structures with wire-like doping with subsequent comparison between calculated data and results of experimental observation of magnetoconductivity, Shubnikov–de Haas oscillations and photoluminescence spectra.

2 Scattering processes

It is obviously to suppose that the leading mechanism of electron scattering in the structures with wire-like doping is the inter- and intrasubband scattering by the random fluctuations of potential relief connected with the presence of ionized Sn impurity. In these conditions when some subbands are filled, the corresponding relaxation times $\tau_{t\alpha}$ of carriers momentum are given by the equation

$$\tau_{t\alpha} P_{\alpha\alpha} - \sum_{\alpha' \neq \alpha} P_{\alpha\alpha'} \tau_{t\alpha'} = 1 \tag{1}$$

where α is the number of the subband.

The probabilities of the corresponding transients $P_{\alpha\alpha}$ can be written within the framework of the Born approximation in the low-temperature limit of scattering on ionized impurity [5]:

$$P_{\alpha\alpha} = \frac{1}{2\pi\hbar E_{F_\alpha}} \int_0^{2k_{F_\alpha}} \frac{\langle |U_1(q)| \rangle^2 q^2 dq}{\varepsilon^2(q)\sqrt{4k_{F_\alpha}^2 - q^2}}$$
$$+ \sum_{\alpha' \neq \alpha} \frac{1}{2\pi\hbar E_{F_\alpha}} \int_{|k_{F_\alpha} - k_{F'_\alpha}|}^{k_{F_\alpha} + k_{F'_\alpha}} \frac{\langle |U'_1(q)| \rangle^2 dq 2k_{F_\alpha}^2}{\varepsilon^2(q)\sqrt{4k_{F_\alpha}^2 - \left[q + \frac{k_{F_\alpha}^2 - k_{F'_\alpha}^2}{q}\right]^2}} \tag{2}$$

$$P_{\alpha\alpha} = \frac{1}{2\pi\hbar E_{F_\alpha}} \int_{|k_{F_\alpha} - k_{F'_\alpha}|}^{k_{F_\alpha} + k_{F'_\alpha}} \frac{\langle |U'_1(q)| \rangle^2 (k_{F_\alpha}^2 + k_{F'_\alpha}^2 - q^2) dq}{\varepsilon'^2(q)\sqrt{4k_{F_\alpha}^2 - \left[q + \frac{k_{F_\alpha}^2 - k_{F'_\alpha}^2}{q}\right]^2}} \tag{3}$$

where E_{F_α} and k_{F_α} are the Fermi energy and the Fermi wave vector, respectively, q is the scattering wave vector, $\langle |U'_1(q)| \rangle$ is the Fourier transform of the potential of electron-ionized impurity interaction, $\varepsilon'(q)$ is the dielectric constant of electron gas. But it should be noted that there is the complementary scattering mechanism of electrons in the GaAs(0.3°,δ-Sn) structure. The spatial quasiperiodic modulation of quantum size levels $\delta E_\alpha(r)$ because the quasiperiodic modulation of impurity distribution $\Delta N_D(r)$ in the δ-doping plane is observed; these fluctuations work as a scattering potential:

$$\delta E_\alpha(r) = \frac{\partial E_\alpha}{\partial N_D} \Delta N_D(r). \tag{4}$$

For a quantum well of triangular shape the variational approach gives us the expression for the first size-quantized level:

$$E_0(r) = \left(\frac{\pi^2 2\hbar e^2}{\chi \sqrt{m^* n_{\mathrm{D}}(r)}} \right)^{2/3}. \tag{5}$$

As the impurity distribution has the Gaussian form their autocorrelation function may be expressed as (in the δ-doping plane):

$$\langle \Delta N_{\mathrm{D}}(r) \Delta N_{\mathrm{D}}(r') \rangle = (N_{\mathrm{D}}^{\max})^2 \left(1 - 2e^{-\lambda^2/8\sigma^2}\right)^2 \exp\left[-\frac{(r - r')^2}{\lambda^2} \right] \tag{6}$$

where $\langle \ldots \rangle$ means an ensemble average.

From Eqs. (4), (5) and (6), the square of the 2D scattering matrix element M_R^2 for the electrons of the first subband can be written as

$$M_R^2 = \pi \left(\frac{2\pi^2 \hbar e^2 N_{\mathrm{D}}^{\max}}{\chi \sqrt{m^*}} \right)^{4/3} \left(1 - 2e^{-\lambda^2/8\sigma^2}\right)^2 \lambda^2 e^{-q^2\lambda^2/4} \tag{7}$$

where $\boldsymbol{q} = \boldsymbol{k} - \boldsymbol{k}'$ is the 2D scattering wave vector and $q = |\boldsymbol{q}|$. In these conditions, the inverse of the transport relaxation time $\tau_t^{\mathrm{LS}}(E)$ due to the scattering by quasiperiodic fluctuations of potential profile in the $[\bar{1}10]$ direction is then given by

$$\frac{1}{\tau_t^{\mathrm{LS}}(E)} = \frac{m^*}{2\hbar} \left(\frac{2\pi^2 e^2 N_{\mathrm{D}}^{\max}}{\chi \sqrt{m^* \hbar}} \right)^{4/3} \lambda^2 \left(1 - 2e^{-\lambda^2/8\sigma^2}\right)^2 \int \frac{e^{-q^2\lambda^2/4}}{\varepsilon^2(q)} (1 - \cos\theta) d\theta \tag{8}$$

where θ is the scattering angle. Thus, the mobility μ_{LS} limited by quasiperiodic scattering may be expressed as

$$\mu_{\mathrm{LS}} = \frac{e}{m^*} \langle \tau_t^{\mathrm{LS}} \rangle. \tag{9}$$

3 Results and discussion

The numerical calculations of the subband relaxation times $\tau_{t\alpha}$ restricted by the impurity scattering have been realized according to Eq. (1)–(3). The values of both the the amplitude of the self-consistent wave function $\xi_{s\alpha}(z)$ and the concentration of electrons from size-quantized levels in the GaAs(0.3°, σ-Sn) structure have been used in the calculations. The values $\tau_{t1} = 1.3 \times 10^{-12}$ s, $\mu_1 = 3500\,\mathrm{cm^2/V\,s}$ and $\tau_{t2} = 2.2 \times 10^{-12}$ s, $\mu_2 = 5800\,\mathrm{cm^2/V\,s}$ have been obtained for the electrons of the first subband and the second one, correspondingly. These values are very close to the experimental data $\langle \mu^{\mathrm{pa,pe}} \rangle = (2{-}7.4) \times 10^3\,\mathrm{cm^2/V\,s}$.

Thus, the physical mechanism restricting the electron mobility in the GaAs(0.3°, σ-Sn) structure is the scattering by the ionized impurity which creates the σ-shape quantum well immediately. But the investigations of the complementary mechanism—electrons scattering by the quasiperiodical fluctuations of potential relief—are still needed.

The parametrical dependences $\tau_t^{\mathrm{LS}}(N_{\mathrm{D}}, \sigma, \lambda, T)$ have been calculated according Eq. (7), (8) for the structures with wire-like doping. The data are presented in Fig. 3. It has been shown by calculations that the low-temperature transport relaxation times of electrons τ_t^{LS} in these structures are in the range $\sim 10^{-11}{-}10^{-12}$ s for $N_{\mathrm{D}} = (1{-}3) \times 10^{12}\,\mathrm{cm^{-2}}$,

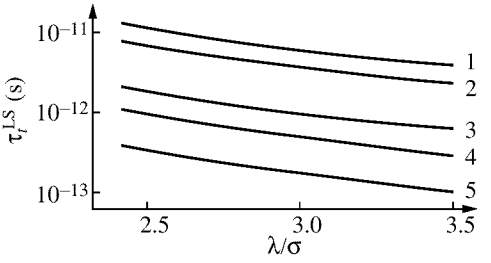

Fig. 3. Calculated parametrical dependences of the transport relaxation time $\tau_t^{LS}(N_D, \sigma\lambda, T)$. $T = 4.2$ K. λ, nm: 1, 2—53, 3—45, 4, 5—40. N_D, cm^{-2}: 1—1×10^{12}, 2, 3, 4—1.4×10^{12}, 5—3×10^{12}.

$\lambda = 40-53$ nm, and $\sigma = (0.3-0.4)\lambda$. thus, the scattering by quasi-periodical fluctuations of potential relief must be taken into account in the modeling of kinetics effects in the wire-like doped structures without one-dimensional channels. It should be noted that the procedure of relaxation times calculation must be modified in respect to the Eq. (4)–(8) in the case when the carriers sense the superlattice potential i.e. the mean free path length is more than the superlattice period [6]. Moreover, the calculations procedure changes if we take into consideration the real (not triangular) shape and finite depth of the quantum well created by wire-like doping; it is the subject of the further investigations.

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